The current state and the future of robotic surgery in female pelvic medicine and reconstructive surgery

Rachael D. Sussman, Benoit Peyronnet, Benjamin M. Brucker

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ABSTRACT

In this article, we review the current uses and future directions of robotic surgery in the field of female pelvic medicine and reconstructive surgery. Pelvic surgery is ideal for the use of surgical robots, which provide improved visualization and ease of suturing deep within the pelvis. Robots have been successfully used for the treatment of pelvic organ prolapse, in procedures such as sacrocolpopexy, sacrohysteropexy, and uterosacral ligament plication. Surgeons have used the robotic successfully to treat various etiologies of female pelvic pain including fibroids, endometriosis, and nerve entrapment. Robotic repair of iatrogenic injury has been described with excellent outcomes and avoidance of conversion to open surgery in the event of an injury caused using the robotic platform. While more data is needed on this topic, there has been increasing interest in using the robot for urologic reconstruction including repair of vesico-vaginal fistula, cystectomy, augmentation cystoplasty, and continent and non-continent diversions. Recently the use of the robot has been described in the treatment of stress urinary incontinence in females, with robotic placement of an artificial urinary sphincter. While robotic surgery is associated with increased cost, the outcomes of robotic surgery in female urology are promising. More studies that properly evaluate the benefits of robotic surgery as compared to open and laparoscopic approaches are needed.

Keywords: Artificial urinary sphincter; neurogenic bladder; pelvic organ prolapse; robotic surgery; sacrocolpopexy; stress; urinary incontinence; vesico-vaginal fistula.

Introduction

Minimally invasive surgery began with the first reported laparoscopic cholecystectomy in 1984 and since that time, its use has revolutionized surgery.[1] The advantages of minimally invasive surgery include smaller incisions, better cosmesis, decreased postoperative pain, fewer infections, shorter hospital stays, and faster convalescence.[2,3] Standard laparoscopy does have its limitations. These include a loss of tactile feedback, a decline in the natural hand-eye coordination, reduction in dexterity (i.e., non-wristed instruments), and loss of three-dimensional visualization. Additionally, when using laparoscopic instruments, surgeons may notice restricted degrees of motion and a magnification of physiologic tremors that are readily transmitted through the length of rigid instruments.[4]

Surgical robots were first used to improve the precision of neurosurgical biopsies in 1985.[5] Currently, the only robotic surgical system in widespread use is the Da-Vinci Robotic System (Intuitive Surgical, Sunnyvale, CA, USA). While not currently available in the USA, the Telelap ALF-X is an alternative robotic system that is supported by the European Commission and has indications in general surgery, gynecology, urology, and thoracic surgery. The relevant patent for the first generation of the Da-Vinci robot will expire later this year and it is expected that several other console-based robots for laparoscopic multi- and single-port surgery will become available in the market in the next five years, including the Medtronic robot, the Avatera robot, the REVO-I, the Medicaroid, and the Avicenna Roboflex, which has been developed for robotic flexible ureteroscopy.[6]

ORCID IDs of the authors:
R.D.S. 0000-0003-0719-9465;
B.P. 0000-0001-8157-2825;
B.M.B. 0000-0003-1699-3871

Department of Urology, New York University, New York, USA

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Corresponding Author:
Rachael D. Sussman
E-mail:
rachael.sussman@nyulangone.org

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Since its inception, technological advances in robotic surgery have allowed for visualization in three dimensions, increased dexterity, instruments with seven degrees of freedom similar to the intrinsic motion of the human wrist, elimination of physiologic tremors, ergonomic positioning, and a dual-console that allows for collaborative surgical opportunities and safe teaching modalities for the next generation of surgeons.[4,7]

Urologists worldwide have been quick to become facile with the surgical robot as the radical prostatectomy was targeted as an index case for robotic surgery due to improved visualization and ease of suturing deep within the pelvis.[7] In the last few decades, both urologists and gynecologists have extrapolated their robotic pelvic surgery success with radical prostatectomy, and have increasingly utilized the robot for reconstructive purposes. In this article, we will review the current uses and future directions of robotic surgery in female pelvic medicine and reconstructive surgery.

Pelvic organ prolapse

Sacrocolpopexy (SC) is considered by many to be the most definitive repair for vaginal vault prolapse with anatomic success rates of 78% to 100%.[8] Unlike uterosacral ligament suspension or sacrospinous ligament fixation, SC allows for the use of permanent materials instead of relying on native tissue, which may be more attenuated in patients with prolapse. Additionally, SC permits the placement of multiple sutures along the anterior and posterior vaginal walls, which allows for distribution of tension over a wide area. It has also been shown to yield a vaginal axis that is closer to normal when compared to vaginal sacrospinous ligament fixation.[9,10]

Minimally invasive laparoscopic SC was first introduced in 1994.[11] The robotic SC was introduced in 2006,[12] leading to a massive increase in popularity of the minimally invasive approach from a mere 7.1% of SC in 2006[13] to 82% in 2016.[14] A recent review of all SCs performed in the United States between 2010 and 2016 found the minimally invasive approach to be associated with reduced rates of 30-day complications (2% vs 2.7%, p≤0.0001), blood transfusion (OR: 0.33, 95% CI: 0.15, 0.74, p=0.007), prolonged hospitalization (OR: 0.16, 95% CI: 0.12, 0.23, p <0.001), and hospital readmission (HR: 0.62, 95% CI: 0.41, 0.96, p=0.03) when compared to the open abdominal approach.[14]

The robot allows pelvic surgeons to overcome some technical difficulties and the steep learning curve surrounding suturing laparoscopically. The SC is an ideal procedure for a robotic approach because of the suturing and knot tying that is needed and the need for delicate dissection on the sacrum. A recent meta-analysis[15] reviewed 27 studies published between 2006 and 2013 with regard to robotic-assisted SC, and found that objective and subjective cure rates ranged from 84% to 100% and 92% to 95%, respectively. Many studies included in this analysis had only a short-term follow-up, but a sub-analysis of studies with at least medium or long-term follow-up had similarly high success rates. When considering the patients in this meta-analysis who underwent robotic SC that had >24 months of follow-up, they identified only 2 recurrences (0.8%) of apical prolapse out of a total of 246 patients.

Surgical outcomes with the robotic platform have improved with increased experience and have an estimated learning curve of 10-20 procedures, which is significantly steeper than the learning curve reported with laparoscopic SC, where the learning curve has been reported to be as high as 60 cases.[16,17] Both laparoscopic and robotic SC have been found to be less costly than open SC; among minimally invasive approaches laparoscopic SC had been found to be less costly than robotic SC with a mean difference in cost of $1,936 (95% CI, $417-3,454).[18]

Uterine preservation

For women with pelvic organ prolapse who desire surgical repair with uterine preservation, there are various surgical options for which the robotic platform may be beneficial. Uterine preservation may be a good option for patients who desire future fertility or are opposed to hysterectomy for various reasons, such as personal beliefs about the importance of the uterus. However, there is a lack of long-term data on these approaches, which means that there is a lack of information on long-term durability or consequences of subsequent pregnancies or development of gynecologic pathology.

Robotic-assisted sacrohysteropexy with mesh has been shown to be safe and feasible.[19] A recent study reported long-term follow-up after robotic sacrohysteropexy and found that among 37 women who were followed-up for 5 years, 81% had no recurrence of uterine prolapse, 8.1% had recurrent stage 1 prolapse and 10.8% had recurrent stage 2 prolapse, which is similar to reported success from laparoscopic and abdominal approaches.[20] For women desiring uterine preservation and avoidance of mesh, laparoscopic uterosacral ligament plication has been shown to be safe, with an objective cure rate of 80% with a short follow-up of 21 months.[21]

While there is a paucity of data on minimally invasive approaches to prolapse repair with uterine preservation, it is reasonable to assume that the benefits of the robotic approach to SC likely translate to the sacrohysteropexy and uterosacral ligament plication, and may be even more pronounced as suturing and manipulation of the uterus may be easier with the use of the fourth arm of the robot.

Pelvic pain

There are several etiologies of female pelvic pain that are amenable to surgical management, including fibroids, endometriosis, and nerve entrapment. The improved visualization, three-dimensional vision, and smooth and precise movements afforded by the robot deep within the pelvis make use applicable to many of these conditions.

Similar to the adoption of robotic skills by urologists worldwide, many gynecologic pelvic surgeons have also become fascicle with the robot and have adopted its use for the treatment of disorders that cause pelvic pain, such as fibroids and endometriosis. A committee opinion from the Society of Gynecologic Surgeons and the American College of Obstetricians and Gynecologists from 2015[22] recently summarized evidence for the use of the robot in both of these diseases. This report found that while laparoscopic techniques for myomectomy have been shown to decrease postoperative morbidity and allow for a faster recovery, most myomectomies in 2015 were performed via laparotomy. The committee did acknowledge that the robotic system may help overcome limitations such as unfavorable myoma location or patient obesity but they also found observational studies suggesting longer operating times and higher cost for the robotic approach. Overall, the committee found the literature at that time to be insufficient and thought that there was a need for comparative effectiveness studies for robotic-assisted myomectomy. A more recent meta-analysis of robotic-assisted vs. laparoscopic and abdominal myomectomies published in 2018 included 2,852 patients and found that robotic-assisted myomectomy is associated with significantly fewer complications and lower estimated blood loss than laparoscopic and abdominal approaches.[23]

Conventional laparoscopy has been used for decades in the treatment of endometriosis, a disorder caused by the presence of endometrial glands and stroma outside the uterine cavity, which can lead to chronic pain. A recent retrospective review comparing robotic and conventional laparoscopic surgery for Stage III or IV endometriosis by a single surgeon found that the perioperative outcomes for the robotic approach were comparable to conventional laparoscopy, but were also associated with increased operating time. However, this group did not account for case complexity while accounting for surgical time. Another retrospective review found that while the operating time for the robotic approach was significantly higher, these patients were more complex and that on multivariate analysis, the operating time was increased by 16.2% when the operation was performed using laparoscopy instead of the robotic approach. This group also found that the operating time was an independent and significant factor for postoperative complications and hospital stay, suggesting a potential improvement in outcomes with the use of the robot due to decreased surgical time.[24] The da-Vinci robot also allows for "Fire Fly" mode, an integrated fluorescence imaging capability [used in conjunction with indocyanine green (ICG)], which uses near-infrared technology and provides real-time, image-guided identification of key anatomical landmarks, bilateral ureters, and endometriotic lesions and may aid in the surgical treatment of this disease.[25]

Pudendal nerve entrapment syndrome is a cause of pelvic pain characterized by unilateral or bilateral neuropathic pain along the distribution of the pudendal nerve, which is caused by compression of the nerve at different levels along its course.[26] It has been shown that decompression of the pudendal nerve is an effective and safe treatment, which can be done through a transgluteal, trasnperineal, or laparoscopic transperitoneal approach. The laparoscopic approach allows for better exploration of the sacral roots of the pudendal nerve and concomitant evaluation for other causes of pelvic pain. The first report of a robotic pudendal nerve decompression was in 2015.[27] These authors found that the robotic advantages of dexterity and magnification over the pure laparoscopic technique were extremely useful in such types of difficult and precise surgery deep within the pelvis.

For patients with midline pelvic pain unresponsive to medical management, presacral neurectomy has been shown to be successful.[28] This involves excision of a segment of the superior hypogastric plexus over the sacral promontory, which interrupts the pain impulses from the cervix, uterus, and proximal portions of the fallopian tubes. In order to minimize intra-operative complications and maximize long-term results, clear identification and gentle dissection of the superior hypogastric plexus is required.[29] With the advancement of minimally invasive techniques, there has been a renewed interest in pelvic denervation procedures for chronic pelvic pain, especially as minimally invasive techniques can be performed with a lower rate of postoperative morbidity as compared to laparotomy.[30] The robotic approach has been shown to be safe and effective,[30] and the improved visualization, three-dimensional vision, and smooth and precise movements afforded by the robot make this procedure more accessible to surgeons who are comfortable with robotic surgery.

Iatrogenic injury

Injury to the urinary tract is a known complication of gynecologic surgery. With an increasing number of gynecologic surgeons performing robotic surgery, it may be advantageous for the urologist to have experience repairing these injuries robotically, when they are identified intra-operatively, to avoid the need for conversion to open surgery or the waste of time that occurs during docking and undocking of the robot to con-

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vert to conventional laparoscopy. A recent retrospective review found that the rates of overall urologic injury during robotic hysterectomy are similar to those reported for laparoscopic hysterectomy, with an overall rate of 0.92% for the robotic hysterectomy as compared to 0.90% for the laparoscopic hysterectomy, 0.33% for the vaginal hysterectomy, and 0.96% for the open hysterectomy.[31] A recent review of the American College of Surgeons-National Surgical Quality Improvement Program database particularly assessed the rate of ureteral injury between 2005 and 2013, and found 302 iatrogenic ureteral injuries from 95,538 hysterectomies with rates of 0.18%, 0.48%, and 0.04% from abdominal, minimally invasive, and vaginal hysterectomy, respectively.[32]

If an injury occurs and it is not identified and repaired intraoperatively, patients are often referred for delayed repair. Robotic-assisted reconstructive surgery of the distal ureter has all of the advantages of minimally invasive surgery. Robotic approaches to reconstruction of the distal ureter have been found to be feasible without compromising the generally accepted principles of open surgery, with good functional outcomes for uretero-neocystotomy by the usage of both the psoas hitch and the boari flap.[33]

Vesico-vaginal fistula

Vesico-vaginal fistulas can be repaired through a vaginal or an abdominal approach, depending upon fistula characteristics and the surgeon's preference and skills. An abdominal approach may be favored for high supratrigonal fistulas and in cases where there is a recurrence after a vaginal repair.[34] The robotic approach has been increasingly used over the past decade to facilitate an abdominal approach to vesico-vaginal fistula repair, with various techniques described. These include transvesical and extravesical repairs, with or without interposition of omental, epiploic, or peritoneal flaps.[35-37] The utilization of fibrin sealant instead of tissue interposition has also been reported.[38]

In a series comparing 12 robotic cases to 20 open abdominal cases, Gupta et al found that the robot-assisted approach was associated with better peri-operative outcomes than patients undergoing open repair without compromising the results.[39] Overall, robotic vesico-vaginal fistula repair seems to provide satisfactory outcomes with insufficient data to determine the most effective surgical steps (i.e., transvesical vs intravesical; interposition vs no interposition etc.). Studies comparing vaginal vs. robot-assisted abdominal vesico-vaginal repair are also lacking.

Complex bladder reconstruction

The management of patients with end-stage bladders due to refractory overactive bladder, interstitial cystitis, radiation cystitis, or neurogenic bladder may involve surgical reconstructions of the lower urinary tract, with complex procedures such as augmentation cystoplasty, ileal conduit, and a catheterizable channel.[40] All these procedures have been reported to carry a relatively high risk of complications within the neurologic population.[41] Over the past decade, several reports have described the use of a robotic approach for these surgical procedures with intent of minimizing the surgical morbidity of lower urinary tract reconstruction in neurogenic patients.[42,43]

Augmentation cystoplasty

Augmentation cystoplasty has traditionally been performed using a detubularized ileal segment.[44] While "clam" augmentation cystoplasty was favored until the 1990s', bladder augmentation is now usually combined with supratrigonal cystectomy.[40,44] Open augmentation cystoplasty is associated with a relatively high rate of peri- and post-surgical complications.[45] The robot-assisted approach has been explored as an alternative to the open approach in order to minimize the surgical morbidity of augmentation cystoplasty,[46] especially the postoperative ileus, which is one of the most common postoperative complications.[45] While several reports have demonstrated the feasibility of robotic augmentation cystoplasty, all these studies are small-sample retrospective series and most of them were conducted in pediatric populations.[47]

To our knowledge, only three series of robotic augmentation cystoplasty in adult patients have been published to date.[46,48,49] The findings of these three series are summarized in Table 1. Gould and Stoffel[46] reported 5 cases with intracorporeal diversion, Madec reported 19 with extracorporeal diversion for both neurogenic bladder and bladder pain syndrome indications, and Flum et al.[49] reported 21 patients with intracorporeal diversion including 7 with concomitant catheterizable channel creation. Overall, all three series reported satisfactory outcomes, although operative time of robotic surgery was longer than open series, with relatively high rates of postoperative complications.

Catheterizable channel

The Mitrofanoff and Monti catheterizable channel is used in patients with urinary retention who are unable to self-catheterize through the urethra, most often due to neurologic conditions with associated motor impairment of the upper limbs.[40] Several pediatric series have demonstrated the feasibility of robot-assisted appendico-vesicostomy and Monti catheterizable channels[50] with two adult series, both of which reported concomitant robotic augmentation cystoplasty in most cases.[49,51] The channel was harvested and/or created intracorporeally in both series and extravesical Lich-Gregoire re-implantation was

Table 1. Series of robot-assisted reconstructive procedures for neurogenic lower urinary tract dysfunction in adult patients

Study	Number of patients	Mean age (years)	Introcorporeal vs. Extracorporeal diversion	Mean operative time (minutes)	Postoperative complications (%)	Mean length of stay (days)	Mean follow-up (months)	Functional outcomes	Long-term complications
Augmentation cystoplasty									
Gould and Stoffel[46]	5	43.8	Intracorporeal	380	60%	7	3	20% failure (persistent vesico-ureteral reflux)	NR
Madec et al.[48]	19	49	Extracorporeal	288.7	47.4%	9.4	13.6	Bladder pain syndrome (n=6): all improved Neurogenic bladder (n=13): 1 failure	10.5%
Flum et al.[49]	21	30	Intracorporeal	365	38.9%	6	38.9	47.9% decrease in bladder pressure	NR
Ileovesicostomy									
Vanni and Stoffel[53]	8	53	Extracorporeal	330	62.5%	8	15	80% with resolved urinary incontinence 0% persistent hydronephrosis	One stomal complication One persistent
Dolat et al.[54]	4	45	Intracorporeal	289.5	12.5%	7.5	25.8	75% with low stomal leak point pressure	One persistent high post-void residual
Cystectomy+ileal conduit									
Deboudt et al.[43]	40	58.6	Extracorporeal	299	35%	10.9	21.9	NR	40%

NR: Not reported; NA: Not applicable

done. An intravesical, posterior bladder wall appendico-vesical anastomosis was described as an alternative in pediatric patients when a concomitant augmentation cystoplasty is performed.[52] As for robotic augmentation cystoplasty, the available data are too scarce to draw robust conclusions on the benefits of robot-assisted surgery as compared to open catheterizable channel creation.

Ileovesicostomy

Ileovesicostomy is a non-continent urinary diversion that remains popular in several centers in North America. It is used to manage high-pressure neurogenic bladders in patients who are unable or unwilling to self-catheterize.[53,54] Two small-sample series have reported robotic ileovesicostomy with the harvest of a segment of distal ileum, which is then anastomosed to the posterior bladder through a robot-assisted approach. The distal end of the ileal segment is then matured as a stoma on the anterior abdominal wall. The main findings of these two series are summarized in Table 1. Comparing their open and robotic cases, Vanni and Stoffel[53] found similar surgical outcomes, although inpatient costs were higher in the robotic group.

Cystectomy and ileal conduit

In some patients with an end-stage bladder, an ileal conduit might be considered, especially in those who are unable to self-catheterize with a high-pressure bladder, have detrusor sphincter dyssynergia, or have an acontractile detrusor.[40] Cystectomy may be associated with this urinary diversion to avoid the relatively high risk of pyocystitis, pain, and cancer when the bladder is left as such in situ.[40] Deboudt et al.[43] reported a single center comparison of robotic vs. laparoscopic vs. open cystectomy and ileal conduit in patients with neurogenic bladder. The authors found that the robotic approach was associated with a longer operative time but showed decreased rates of hemorrhagic complications and long-term reoperations.[43]

Stress urinary incontinence

Artificial urinary sphincter implantation

While AMS-800 artificial urinary sphincter (AUS) implantation is unanimously recognized as the gold-standard in surgical treatment for male patients with severe stress urinary incontinence due to intrinsic sphincter deficiency (ISD),[55,56] its use in female patients remains very limited in most countries, especially in

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Table 2. Series of robot-assisted artificial urinary sphincter implantation in women

Study	Number of patients	Bladder neck injury (%)	Vaginal injury (%)	Mean length of stay (days)	Postoperative complications (%)	Major (Clavien≥3) complications (%)	Mean follow-up (months)	Explantation* (%)	Revision* (%)
Fournier et al.[62]	6	0%	0%	6	16.7%	0%	14.3	0%	0%
Biardeau et al.[65]	9[a]	22.2%	22.2%	4.9	33.3%	22.2%	18.9	22.2%	0%
Peyronnet et al.[63]	8	25%	12.5%	3.5	25%	12.5%	5	12.5%	0%
Peyronnet et al.[64]	49	10.2%	6.1%	4	18.3%	4.1%	18.5%	2%	6.1%

[a]only AUS implantations are presented (the two revisions were excluded)

places where pubovaginal slings or bulking agents are favored.[57,58] Despite good functional outcomes and high rates of patient satisfaction, AUS has not been widely used in female patients due to the technical difficulty of its implantation via an open retropubic approach and the highly inherent morbidity.[57,59] The main technical challenge of AUS implantation in female patients lies in the dissection of the bladder neck, which needs to be clearly separated from the vaginal wall in order to place the cuff. Many surgeons choose to do this dissection abdominally in order to avoid a vaginal incision but the dissection itself is particularly difficult, as the space is located deep in the female pelvis, with many small blood vessels that may impair visualization and limit the dexterity, which in turn may impair the ability of the surgeon to place surgical instruments at a proper angle for easy dissection.

In an effort to minimize technical complexity, laparoscopic AUS implantation in female patients was described in the late 2000s with promising preliminary results when performed by experienced hands.[60,61] More recently, several series have reported the use of a robotic approach for female AUS implantation, which allows for the benefits of minimally invasive surgery with lower technical complexity as compared to laparoscopic surgery. Enhanced dexterity with the endowrist technology allows for multiple dimensions mobility of the instruments, a magnified 3D image, physiologic tremor filtering, and motion scaling of the surgical robot, all of which help to minimize the technical complexity of performing robotic AUS.[62-65]

In a preliminary series of six cases, Fournier et al.[62] reported promising outcomes with no explantations or erosions and found 83.3% of patients to be fully continent post-operatively. Using the same robotic technique with the assistant's finger placed in the vaginal fornix to expose the vesico-vaginal plane, Peyronnet et al.[63] later reported eight robotic cases and observed a significant decrease in postoperative complications as compared to their open cohort (25% vs. 75%; p=0.02), with a reduced length of hospital stay (3.8 vs. 9.3 days; p=0.09). The excellent outcomes of this technique were further confirmed in a multicenter series of 49 cases with a minimum 12 months follow-up. In this complex patients' population with 85.7% having an history of previous anti-incontinence surgery, the authors reported only one explantation (2%) with 81.6% of patients fully continent after a median follow-up of 18.5 months.[66] Using a slightly different technique, without the help of the assistant's finger and with the cuff placed more distally toward the mid-urethra, Biardeau et al.[65] reported 9 cases with less favorable outcomes, including a 22.2% rate of erosion, highlighting the need of standardized surgical steps in addition to the robotic approach to decrease female AUS implantation surgical morbidity. The main outcomes of these 4 robotic series are summarized in Table 2. Despite the high-level evidence, studies supporting the use of female AUS are still lacking.[64] Easier implantation through a robotic approach and a new generation of electromechanical implants without a pump required in the labia majora may pave the way for increasing popularity of female AUS in the near future.

Burch colposuspension

The use of the Burch colposuspension has largely dwindled over the past twenty years due to the widespread adoption of mid-urethral slings as the first-line surgical treatment for female patients with stress incontinence. However, recent FDA notifications regarding the use of mesh for vaginal repair of pelvic organ prolapse have led to an increasing demand for options that avoid synthetic materials for all reconstructive procedures. Thus, some surgeons may offer Burch colposuspension to selected patients.[67] Robotic Burch colposuspension has been described in 2015[68] with another case reported in 2017[69] and a small-sample randomized trial has been conducted that compared robotic vs. open abdominal hysterectomy with concomitant Burch procedure, which demonstrated similar outcomes between the two approaches.[70] When compared to a mid-urethral sling, one disadvantage of the Burch colposuspension is that in case of postoperative voiding dysfunction, it is much simpler to cut or loosed a sling compared to removing retropubic sutures. Owing to the cost of robotic surgery, authors

have suggested that robotic Burch colposuspension should be used mostly when a concomitant robotic abdominal procedure is planned.[68-70]

In conclusion, over the past decade, robot-assisted surgery has spread significantly in female pelvic medicine and reconstructive surgery, with almost all the open surgical procedures being performed with the robotic approach. While the outcomes of robotic surgery in this area are promising, studies that properly evaluate the benefits of robotic surgery over open and laparoscopic approaches are still lacking. High-level evidence studies are needed to help determine the role of robotic surgery in female urology. Ongoing development of newer robotic platforms and functional urology devices are likely to impact the use of robotic surgery in functional urology in the near future.

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